

# Nitrogen Overabundance: Globular Cluster and Halo Formation

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## ABSTRACT

Halo globular clusters pose four succinct issues that must be solved in any scenario of their formation: single-age, single metallicity stellar populations; a lower limit ( $[\text{Fe}/\text{H}] \sim -2.3$ ) to their average metallicity; comprising only 1% of the stellar halo mass, and being among the oldest stars in our Galaxy. New spectra are presented of Galactic stars and integrated spectra of Galactic globular clusters which extend to 3250Å. These spectra show that the most metal-poor and among the best-studied Galactic globular clusters show strong NH3360 absorption, even though their spectral energy distributions in the near-UV are dominated by blue horizontal branch, AF-type stars. These strong NH features must be coming from the main sequence stars in these clusters. These new data are combined with existing data on the wide range of carbon and nitrogen abundance in very metal-poor ( $[\text{Fe}/\text{H}] < -3.5$ ) halo giant and dwarf stars, together with recent models of zero-metal star formation, to make a strawman scenario for globular cluster formation that can reproduce three of the above four issues, and well as related two of the three issues pertaining to nitrogen overabundance. This strawman proposal makes observational and theoretical predictions that are testable, needing specific help from the modelers to understand all of the elemental constraints on globular cluster and halo formation.

*Subject headings:* globular clusters, halo stars: chemical abundances, formation

## 1. Introduction

Any theory of globular cluster (GC) formation must be able to explain the following observations: 1. The low mass stars we see today in halo GCs comprise a single-age, single  $[\text{Fe}/\text{H}]$  set of stars, with specific abundance variations among proton-capture elements (e.g., Gratton, et al. 2001). The gas from which these stars formed was not blown away from the winds/supernovae from the more massive stars in these clusters. 2. There appears to be a

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lower limit to the average  $[\text{Fe}/\text{H}]$  of a GC, being near  $[\text{Fe}/\text{H}] = -2.5$  for the most metal-poor clusters in our Galaxy and in other galaxies. 3. GCs comprise about 1% of stellar mass of the halo of our Galaxy. 4. The halo clusters are the oldest stars in our Galaxy, likely formed during the first burst of star formation. Given the age now put on the Universe by the WMAP observations, 13.7 Gyr (Spergel, et al. 2003), and the age estimates for metal-poor GCs ( $\sim 13$  Gyr) (e.g., Grundahl, et al. 2000), it is clear that the halo, most metal-poor GCs (e.g., M92, M15) formed very shortly after recombination.

Recent observations (e.g., Norris, Ryan, & Beers 2001; Norris et al. 2002; Aoki, et al. 2002; Christlieb, et al. 2002) have found that a few halo subgiant and giant stars with  $[\text{Fe}/\text{H}] = -3.5$  to  $-5.3$  have surprisingly high nitrogen and carbon abundances. Such metal-poor stars are almost certainly formed coevally with the halo GCs. Aoki et al. find two of their stars (CS 22949-037 and CS29498-043) have spectroscopic evidence of  $[\text{N}/\text{Fe}] = 2.3 \pm 0.4$ , similar to what was found by Bessell & Norris (1982) for two other stars.

Burstein, et al. (1984) and Ponder et al. (1998) have found both Galactic GCs and M31 GCs to have enhanced CN features (near  $4150\text{\AA}$  and  $3880\text{\AA}$ ) in their integrated spectra. Ponder et al. also show that the NH molecular band at  $3360\text{\AA}$  is very strong in the integrated spectra of four M31 GCs, including 3 of the ones studied by Burstein et al.

YL is in the process of completing a Ph.D. thesis, in which he has obtained spectrophotometry from  $3250\text{\AA}$  to  $1\mu$  at  $10\text{\AA}$  spectral resolution for 125 stars with IUE data, as well as for 8 Galactic GCs. § 2 presents our spectra for these 8 Galactic GCs, together with spectra for the 4 M31 GCs studied in Ponder et al. and the NH, CH,  $\text{Mg}_2$ , and  $[\text{Fe}/\text{H}]$  data for these GCs and graphically for NH, CH and  $[\text{Fe}/\text{H}]$  for the stars in YL's thesis. § 3 combines our results with those for the metal-poor halo stars and presents a strawman scenario for the formation of the oldest stars in our Galaxy which can fit most of the observational issues given above, plus some of those that arise with carbon and nitrogen overabundance in the oldest stars. Equally important, this scenario makes several predictions which can be observationally and theoretically tested.

## 2. Near-UV Observations of Galactic and M31 Globular Clusters, and Galactic Stars

YL's observations of Galactic GCs and stars were made with the Boller & Chivens CCD spectrograph on the 2.3m Bok telescope of the Steward Observatory. Li integrated the light from each GC with a  $4'$  spectrograph slit to synthesize their spectra over a region approximately  $3' \times 4'$  in size. Data for all stars and Galactic GC are fluxes and cover the

wavelength range 3250Å to  $1\mu$  at 10-12Å spectral resolution. Figure 1 presents the integrated spectra from 3250Å to 4900Å that Li has obtained for 8 Galactic GCs, ranging from M92 to M71 in metallicity. The high signal-to-noise (S/N) of YL’s GC observations is evident in the high degree of similarity of the spectra of M92 and M15. Also presented in Figure 1 for completeness are the analogous integrated spectra obtained with the HST/FOS for 4 M31 GCs by Ponder et al.

Tomkin & Lambert (1984) pointed out that NH and CH (the G-band) have essentially the same dissociation energy (a difference of only 0.05 eV), so that a relative comparison of carbon to nitrogen abundance can be made in individual stars by comparing the strength of the molecular bands of these two molecules. Davidge & Clark (1994) and YL’s stellar observations show that NH, like CH, is absent in Galactic stars earlier than F2 or so, and is stronger in giant stars than in dwarf stars.

It is clear from these Figure 1 that the NH molecular band is present in the spectra of all 12 GCs, and is especially strong in the more metal-rich M31 GCs (Mayall II, K280 and K58). What is even more remarkable are the observed NH strengths in M92, M15, M53, among the most metal-poor GCs in our Galaxy: Inversion of the Ca II H&K lines (with H being stronger than K) is indicative of domination of A-F stars near 4000Å (likely due to the blue horizontal branches of these clusters; e.g., Piotto, et al. (2002)), and is seen in the 7 more metal-poor Galactic GC spectra (but not for one metal-rich GC in our sample, M71). Along with early-type Galactic stars, metal-poor stars earlier than F-type do not have NH in their spectra. Moreover, stellar population models indicate that giant stars contribute at most 15% of the flux at 3360Å (R. Peterson, private communication). The enhanced NH features seen in some giant stars in metal-poor GCs (e.g., Suntzeff 1981; Kraft, et al. 1982; Trefzger, et al. 1983; Shetrone, et al. 1999) cannot alone produce the strong NH we see. These strong NH features seen in integrated light must be mostly due to the main sequence stars in these GCs.

In Figure 2 we plot the absorption line strengths of CH (G-band) vs. NH, and CH and NH vs.  $[\text{Fe}/\text{H}]$  for the stars in Li’s thesis, together with those of the 12 GCs shown in Figure 1. The CH data for Galactic and for M31 GCs are taken from (Trager, et al. 1998).  $[\text{Fe}/\text{H}]$  for Galactic GC are taken from the online data given by Harris (e.g., Harris 1996); for stars from the compilation in Worthey, et al. (1994).. The definition given by Davidge & Clark (1994) is used for the NH feature.

Five issues are evident from Figure 2: 1. The CH measures for the all of the Galactic and M31 GC place their indices mostly among the Galactic dwarf stars. 2. NH is clearly enhanced relative to CH,  $[\text{Fe}/\text{H}]$  (and also  $\text{Mg}_2$ , not shown) for the 8 most metal-poor GCs, relative to that observed in Galactic stars. 3. The strength of NH in the MS stars in the

metal-poor clusters has to be stronger than what we see in their integrated light, as the flux in the near-UV in these clusters is dominated by their blue horizontal branch stars. Yet, if we examine the horizontal branch ratio for these clusters (e.g., Harris 1996), we do not find that it correlates with NH strength for the 7 metal-poor Galactic GC. Perhaps there is range of nitrogen abundance among the metal-poor Galactic GC? 4. As a group, NH is far stronger in the 3 more metal-rich M31 GCs than it is in the Galactic GCs at a given value of CH or  $[\text{Fe}/\text{H}]$ . 5. There are three well-known nitrogen-rich stars (HD 122563, HD 165195, and HD 201626, e.g, Sneden (1974); Yorka (1983); Shetrone, et al. (1999)) that have nitrogen abundances as high as those in the *integrated* spectra of the more metal-rich M31 GCs. However, as giant stars do not dominate in the near-UV in these GCs, the mixing that produces the strong NH in these Galactic giant stars cannot be the sole source of the strong NH feature in the M31 GC.

A full analysis of the nitrogen overabundance in these Galactic GCs will require obtaining high S/N spectra of their lower main sequence stars, a task that still remains to be done. However, given that the structure of the NH feature in these GCs is similar to its structure seen in metal-rich stars (like the Sun; e.g., Norris et al. (2002)), we are relatively safe in predicting that for the M31 and Galactic GCs,  $[\text{N}/\text{Fe}]$  ranges from 0.7 to 2.5. For example, *if*  $[\text{N}/\text{Fe}] = 1.7$  in M92 stars, then the N abundance in M92 stars means that the total mass of nitrogen, assuming  $1 - 2 \times 10^5 M_\odot$  of stars, is  $30 - 50 M_\odot$ .

### 3. A Strawman Formation Scenario

We make the reasonable initial assumption that the overabundance of nitrogen seen in a few halo giant stars with  $[\text{Fe}/\text{H}] < -3.5$ , and in the integrated spectra of the most metal-poor Galactic and M31 GCs is primordial in origin. There is simply too much nitrogen overabundance for any secondary enhancement of nitrogen to take place via 5-7  $M_\odot$  asymptotic giant branch stars in these clusters (such as advocated by Larsen, Sommer-Larsen, & Pagel 2002), without appealing to unusual initial mass functions. Hence, to the list of observations that any formation scenario for GCs must fit, given in § 1, we now can add three more: 5. Produce a marked overabundance of nitrogen in the most metal-poor, oldest GCs. 6. Produce a similar marked overabundance of nitrogen in a *subset* of the oldest, most metal-poor halo stars. 7. Produce an intrinsic range of nitrogen abundances between the GCs among different galaxies, and perhaps also among the oldest GCs within a given galaxy.

Our strawman proposal can, in broad-brush strokes, can currently fit 5 of these 7 issues for GCs and halo stars, and can also be consistent with what we know about the early Universe. Cayrel (Cayrel, R. 1986, 1987) outlined much of this scenario; here we expand on

this scenario, given that we have more information than was available in the 1980’s.

We begin with the idea that formation of GCs most likely took place with zero-metal, H+He primordial gas. Then, take into account that the Jean’s mass of this zero-metal gas is  $10^5 - 10^6 M_\odot$  for a long time after recombination (e.g. Rosenblatt, Faber, & Blumenthal 1988, and references therein). Now insert the issue that Norris et al. (2002) brought up, namely, the kind of star can produce such remarkable overabundances of C and N in the oldest stars, that the zero-metal stellar models of Fryer, Woosley, & Heger (2001) seem to fit the CNO issue. These are 200-500  $M_\odot$  zero-metal rotating stars which quickly burn some of their hydrogen to helium, then helium to carbon, then undergo carbon burning of hydrogen. The net effect of this is that when this supermassive star goes hypernova, it expels out many solar masses of CNO product.

Now suppose that modelers can produce a hypernova from zero-metal gas that produces not just C, N and O but also the various other proton capture reactions needed to produce the range of elemental abundances differences seen in Galactic GC (e.g., Gratton, et al. 2001). A tall order to fill, but one that needs to be explored. And also suppose that these new models show that these hypernova produce a range of abundance of CNO, while producing a set amount of higher order metals. Yet another tall order. If each hypernova produces 20-40 solar mass of nitrogen, then perhaps just one hypernova in the centers of  $10^5 - 10^6 M_\odot$  Jean’s mass clumps is needed to produce the nitrogen overabundance we see in the most metal-poor GCs. The most likely place for such zero-metal stars to form is at or near the centers of the zero-metal Jean’s masses that have formed in the early Universe. And, most of those masses will be found within the dark matter confines of what will eventually become a giant galaxy.

In the case of the GCs, these massive stars sit very close to the centers of these Jean’s mass clumps, and their hypernovae go off symmetrically more or less simultaneously seeding the rest of the mass of the clump with its pollutants, and uniformly crunching the gas to make stars out of this gas. The resulting stars will then have a base level of metallicity, and a large overabundance of C and/or N and/or O, of which we clearly see today the N overabundances. As these clumps are close together at early epochs in the Universe, merging of clumps is also likely, producing clusters with bimodal CNO abundances (e.g., Harbeck, Smith, & Grebel 2003).

On the other hand, the likelihood that such symmetry exists in the hypernovae explosions that will occur near the centers of these  $10^6 M_\odot$  zero-metal clumps is small. In fact, given that globular cluster stars comprise only 1% of the halo stars, it is likely a 1% probability. In almost all of the cases, therefore, the hypernovae will go off *asymmetrically*, crunching just some of the remaining gas, but releasing the rest of its energy (and thereby,

if this is true for all galaxies, re-ionizing the Universe). This will result in most halo stars getting different portions of the hypernova elemental products. This, then, can produce the intrinsic range of C and N overabundance that is observed in some, but not all, metal-poor halo stars. It is also likely that formation of this kind also existed in the masses that formed the centers of giant elliptical galaxies, as Trager, et al. (2000a,b) find that N is overabundant in their centers, along with  $\alpha$ -product elements.

This scenario can readily reproduce five of the seven issues discussed above for GC formation. What it cannot reproduce is the apparent systematic difference in nitrogen abundance seen in the present data between the M31 GCs and the Galactic GCs. Nor can it yet reproduce the elemental abundance similarities and differences found among Galactic globular cluster stars versus those in the halo. Rather than take the difference between M31 GC and Galactic GC at face value, we note that these 4 M31 GCs are more luminous than even  $\omega$  Cen in our own Galaxy. NH observations of less luminous M31 globular clusters will be needed, together with observations of many other Galactic GCs and GCs in other galaxies (e.g, the Fornax dwarf galaxy, Large Magellanic Cloud, Cen A, M81), before we can understand if there are true systematic differences in nitrogen abundance among the oldest GCs in different galaxies.

Our scenario for GC and halo star formation makes five testable predictions:

1. Strong NH features should exist in other, metal-poor halo GCs in our Galaxy as well as metal-poor (and old metal-rich) GCs in other galaxies. It remains to be seen how much variation we see among the GCs within a given galaxy, and from galaxy-to-galaxy.

2. The hypernovae that produce the GCs might produce black holes. Depending on how that black hole is fed (and it might be very starved within the beehive that are GCs), its mass might be only 50-100  $M_{\odot}$ , making it very hard to detect in most GCs. In this regard, we note the suggestion that large, massive (2000-20,000  $M_{\odot}$ ) blackholes are in two of the GC for which we show strong NH features: Mayall II (MII in Figure 1) in M31 (van der Marel et al. 2002) and in the metal-poor Galactic GC, M15 (Gebhardt, Rich, & Lo 2002), although these interpretations are being disputed (Baumgardt, et al. 2003a,b).

3. Those GCs that form later in time will not produce such hypernovae, so will not likely show the kind of nitrogen overabundance relative to iron that is seen in the metal-poor globular clusters or the most metal-poor galactic stars. How much younger should these other GCs be? If we say that the oldest GCs are 13 Gyr old, then ones that are, say, 8-9 Gyr old might fit this bill. Hence, much younger GCs should *not* show NH enhancements. The mild oxygen overabundance seen in  $[\text{Fe}/\text{H}] > -1.5$  stars (e.g. Edvardsson, et al. 1993) is consistent with this issue. We note that the data presented here for the younger disk GC

M71, compared to that of its older, more metal-poor cousins, is the most consistent with this prediction among the Galactic GCs.

4. The most metal-poor halo stars should show a continuum of CNO abundances.

5. Zero-metal star models can be made that reproduce the various proton-capture abundance issues that are now known to exist among Galactic GC stars, while preserving their small range in overall  $[\text{Fe}/\text{H}]$  as well as intrinsic N abundance differences among different galaxies. Altogether, a significant challenge for the modelers.

Exploring the observational and theoretical consequences of this halo and GC formation scenario will take the efforts of both observers (near-UV integrated spectra of GCs in our Galaxy and in other galaxies; similar spectra of individual main sequence GC and halo stars in our Galaxy) and theoreticians (to interpret these spectra and to make new zero-metal gas stellar models). We put forward this strawman scenario with the strong likelihood that much of it will have to be modified in the future, if not completely changed. However, we have to start somewhere to understand the now clearly-defined nitrogen-based issues in old stars, and here is where we choose to start.

We thank Donald Lynden-Bell for very stimulating conversations about globular cluster formation scenarios, and John Norris, Mike Bessell and Ken Freeman for helpful suggestions. We also thank the anonymous referee for helpful comments for reshaping this paper.

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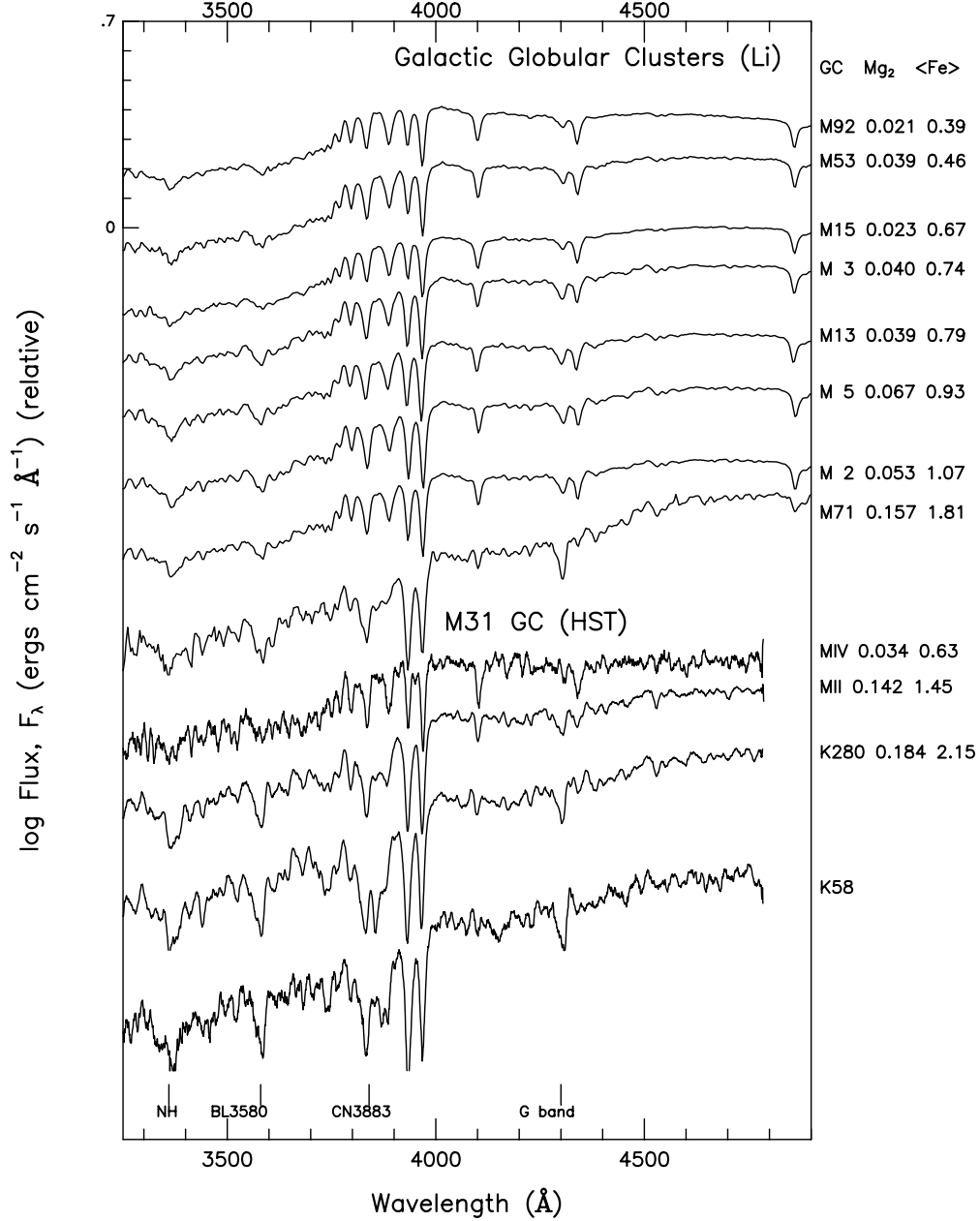


Fig. 1.— Integrated spectra from 3250Å to 4900Å of 8 Galactic globular clusters from Li’s Ph.D. thesis (top) and from 3250Å to 4800Å for 4 M31 globular clusters from Ponder et al. (bottom), plotted as log flux vs. wavelength. Each spectrum is plotted on a log scale of 0.7 dex of flux. The Messier numbers of the Galactic clusters are given. MII and MIV are Mayall II and Mayall IV, 280 and 58 are the Vitesnik numbers for these M31 GCs (cf. Ponder et al. 1998). Also given are the Mg<sub>2</sub> and < Fe > measures for 11 of these clusters from Trager et al. (1998).

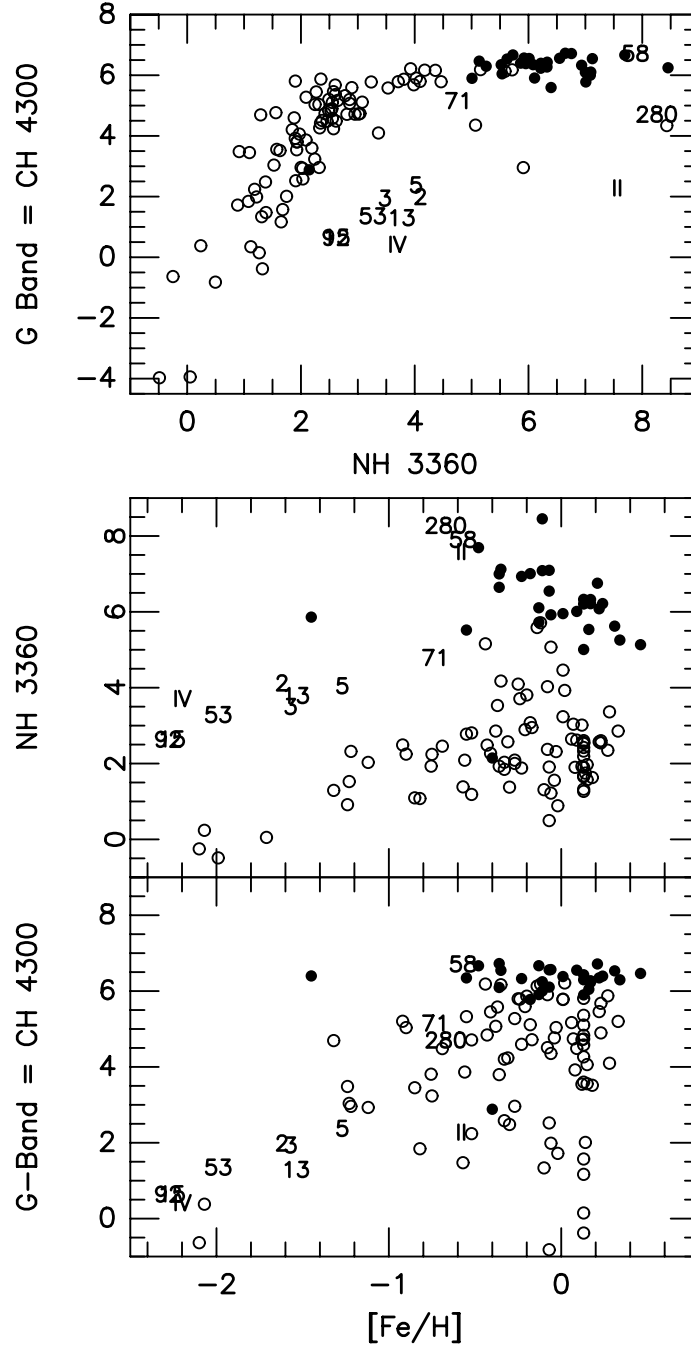


Fig. 2.— (top) The absorption line measure of CH (G-band) plotted versus NH for Galactic dwarf stars (open circles), Galactic giant stars (closed circles), the Galactic GCs (given by their Messier numbers) and M31 GCs (given by their names as listed in Figure 1). The data for the 125 Galactic stars comes from YL’s thesis. (lower two graphs) NH vs.  $[\text{Fe}/\text{H}]$  and CH vs.  $[\text{Fe}/\text{H}]$ . The NH and CH values for the Galactic GC are, in order of Messier number, CH and NH: (2: 1.966,4.099), (3: 1.912,3.476), (5: 2.351,4.022), (13: 1.268,3.766), (15: 0.626,2.621), (53: 1.328,3.262), (71: 5.127,4.767), (92: 0.618,2.612). The strong agreement of the CH and NH values for M15 and M92 indicate the high S/N of our GC spectra.